<u>REMARKS/ ARGUMENTS</u>

The Final Office Action of May 6, 2005 has been carefully reviewed and this response addresses the Examiner's concerns.

<u>Status of the Claims</u>

Claims 1-11 are pending in the application.

Claim 11 was withdrawn.

Claim 9 is amended in order to correct an informality.

Claims 1-10 were rejected under 35 U.S.C. §102(b) as being anticipated by U.S. Patent 6,166,838 (the '838 patent) to Liu et al.

<u>The 35 U.S.C. §102 rejection</u>

Claims 1-10 were rejected under 35 U.S.C. §102(b) as being anticipated by U.S. Patent 6,166,838 to Liu et al.

Applicants respectfully request the Examiner reconsider the rejection of claims 1-10 based upon the remarks set forth herein and below.

In order to clearly point out the novelty (and, incidentally, nonobviousness) of the present invention, Applicants present the basis for such novelty by a <u>specific</u> comparison between the teachings of the '838 patent and the elements of the presently claimed invention, more specifically, as presented by exemplary independent claims 1 and 8.

In the Applicants' claimed invention, an optical switch/variable attenuator includes a polarization separating subsystem that receives and input optical beam of arbitrary polarization and emits two optical beams of the same polarization, one or more switchable diffraction gratings receiving the two optical beams of the same polarization, and a polarization recombining subsystem that receives the receives the optical beams of the same polarization transmitted by the one or more switchable diffraction gratings and outputs one or more final output beams of combined polarization.

Liu et al., in Fig. 3a of the '838 patent, teach an add/drop wavelength switch including a first birefringent element 200 capable of spatially separating the horizontal and vertically polarized components of these signals 700, 701 (Fig. 3a, the '838 patent) (according to the '838 patent, col. 4, lines 24-26, a polarization beam splitter can also be used to perform a similar function for polarization separation as the birefringent element), a fixed polarization rotator 301_1 capable of rendering the state of polarization (SOP) horizontal, a switchable (e.g. in response to a control bit) polarization rotator 301_ 2 under control of a control bit and capable of selectively rotating the polarization of the add signal 701 by a predefined amount, a first stacked waveplates element 400 is made of a stacked plurality of birefringent, composite waveplates at selected orientations that generate two eigen states, a second birefringent element 201, a second set of polarization rotators 302_1 and 302_2 that follow the second birefringent element 201, a third birefringent element 202, a second stacked waveplates element 401 that has the same structure and composition as to the first stacked waveplates element 400, a third set of polarization rotators 303_1 and 303_2 and a fourth birefringent element 203, where the two orthogonal polarizations are recombined by the fourth birefringent element 203 (col. 4, lines 11-67, col. 5, col. 6, lines 1-25, the '838 patent).

In comparing the teachings of the '838 patent to the Applicants' claimed invention, in order to avoid the use of terms in a manner inconsistent with their meaning as understood by one of ordinary skill in the art, it is essential to define the meaning that one of ordinary skill in the art would give to some of the terms, such as "polarization rotator," "birefringent element" and "waveplate." Thus, a "polarization rotator" is a component "that receives a beam of radiation of any arbitrary polarization angle and produces a new beam, coaxial with the incident beam, having a specified new polarization angle" (from The Photonics Dictionary available at http://www.photonics.com/dictionary/lookup/XQ/ASP/url.lookup/entrynum.2473/letter.i/pu./QX/lookup.htm). Examples of switchable polarization rotators are rotators using liquid crystal based technology (a preferred embodiment according to '838 patent, col. 4, lines 48-49). (See, for example, www.displaytech.com/products/photonics/rot_pol.html, a copy of which is provided in the Appendix). "Birefringence" is defined as the separation of light into two beams, where each of the two beams is polarized in a direction opposite to the other beam (see, for example, The Photonics Dictionary available at

http://www.photonics.com/dictionary/lookup/XQ/ASP/url.lookup/entrynum.496/letter.b/pu./QX/lookup.htm or Hecht, Optics, ISBN 0-201-11609-X, p. 286, copies of which are attached in the Appendix).

A "waveplate," as defined in any introductory optics book such as Hecht, Optics, is an "optical element having two principal axes, slow and fast, that resolve an incident polarized beam into two mutually perpendicular polarized beams, which the emerging beam recombines [the two beams] to form a particular single polarized beam" (see, for example, The Photonics Dictionary available at http://www.photonics.com/dictionary/lookup/XQ/ASP/url.lookup/entrynum.5639/letter.w/pu./QX/lookup.htm or Hecht, Optics, ISBN 0-201-11609-X, pp. 300-304, copies of which are attached in the appendix).

In order to aid the Examiner in identifying such inconsistencies, Applicants first provide a listing of the limitations of claim 1 of the Applicants' invention. Claim 1 of the Applicants' claimed invention includes

(a) a polarization separating sub-system, said polarization separating sub-system being optically disposed to receive an input optical beam of arbitrary polarization and also being capable of separating the input optical beam into a first optical beam of a first polarization and a second optical beam of a second polarization, said second polarization being distinct from said first polarization, and emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization, said emitted first and emitted second optical beams constituting an input channel of the first polarization;

(b) at least one switchable diffraction grating, said at least one switchable diffraction grating being optically disposed to receive the input channel and capable of providing at least one transmitted channel, the at least one transmitted channel comprising at least one transmitted optical beam of the first polarization and at least one other transmitted optical beam of the first polarization; said at least one switchable diffraction grating constituting a set of switchable diffraction gratings;

(c) means for varying a diffraction efficiency of said at least one switchable diffraction grating; and

(d) a polarization recombining sub-system, said polarization recombining sub-system

being optically disposed to receive the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization and capable of recombining the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization into at least one final output beam.

Second, each of the limitations of claim 1 of the Applicants' invention is compared to the teachings of the '838 patent as identified by the Examiner.

The Examiner identifies element 200 or 201 in Figure 3a of the '838 patent (col. 4, lines 11-26, the '838 patent) as teaching the first limitation of claim 1 in the Applicants' invention. Comparing the first limitation of claim 1 of the Applicants' claimed invention to the birefringent element 200 or 201 disclosed in Fig. 3a of the '838 patent, the Applicants claim a system including a polarization separating sub-system capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first (<u>same</u>) polarization, while <u>the birefringent element 200 or 201 of Fig. 3a of the '838 patent emits</u> two beams, where each of the two beams is polarized in a direction opposite to the other beam, that is, <u>two beams of different polarization</u>. Applicants respectfully submit that the fourth birefringent element 200 or 201 in Fig. 3a of the '838 patent does not perform the same function, or in the same way, or provide the same result as the polarization separating sub-system of claim 1 in the Applicant's invention. <u>Therefore, the '838 patent does not teach, explicitly or implicitly, a polarization separating sub-system capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization.</u>

The Examiner identifies the polarization rotator 301_2 in Fig. 3a of the '838 patent (col. 4, lines 32-50, the '838 patent) with the second limitation of claim 1 of the Applicant's invention, the at least one switchable diffraction grating. Diffraction, an effect characteristic of wave phenomena, defined by Grimaldi in the 1600s, is the deviation of light from rectilinear propagation resulting from the encountering of an obstacle, either transparent or opaque, by a region of the wavefront (see, for example, Hecht, Optics, ISBN 0-201-11609-X, p. 392, a copy of which is attached in the appendix). A grating is an array of diffracting

elements (see, for example, Hecht, Optics, ISBN 0-201-11609-X, p. 424, a copy of which is attached in the appendix). Comparing the polarization rotator 301_2 in Fig. 3a of the '838 patent to the second limitation of claim 1 of the Applicants' invention, the at least one switchable diffraction grating, the polarization rotator 301_2 "produces a new beam, coaxial with the incident beam, having a specified new polarization angle" while, in the switchable diffraction grating, the direction of propagation of the output beam (or beams) deviates from the direction of propagation of the incoming beam. Applicants respectfully submit that the polarization rotator 301_2 in Fig. 3a of the '838 patent is not a switchable diffraction grating. <u>Therefore, the Applicants respectfully submit that the '838 patent does not teach or disclose, explicitly or implicitly, at least one switchable diffraction grating.</u>

Since the polarization rotator 301_2 is not a switchable diffraction grating, the means for switching the polarization rotator 301_2 in Fig. 3a of the '838 patent are not means for varying a diffraction efficiency of the at least one switchable diffraction grating. <u>Therefore, the Applicants respectfully submit that the '838 patent does not teach or disclose, explicitly or implicitly, means for varying a diffraction efficiency of said at least one switchable diffraction grating.</u>

The Examiner identifies the fourth birefringent element 203 in Fig. 3a of the '838 patent (col. 6, lines 25-32, the '838 patent) with the fourth limitation of claim 1 of the Applicants' invention, a polarization recombining sub-system capable of capable of recombining the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization into at least one final output beam of combined polarization. The fourth birefringent element 203 in Fig. 3a of the '838 patent <u>recombines two orthogonal polarizations into one output beam</u> while <u>polarization recombining sub-system of claim 1</u> in the Applicant's invention <u>recombines</u> the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization (<u>the same polarization</u>) into at least one final output beam. Applicants respectfully submit that the fourth birefringent element 203 in Fig. 3a of the '838 patent does not perform the same function, or in the same way, or provide the same result as the polarization recombining sub-system of claim 1 in the Applicant's invention. <u>Therefore, the Applicants respectfully submit that the '838 patent does not teach or disclose, explicitly or implicitly, a polarization</u>

recombining sub-system capable of capable of recombining the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization into at least one final output beam of combined polarization.

The differences between the limitations of claim 1 of the Applicants' invention and the '838 patent are summarized in Table 1, a copy of which is attached in the Appendix.

Applicants respectfully assert that the '838 patent (Liu et al.) does not disclose, expressly or inherently, at least one patentable limitation (element) of claim 1. Since claims 2-7 are dependent on claim 1, Applicants respectfully assert that the '838 patent (Liu et al.) does not disclose, expressly or inherently, at least one patentable limitation (element) of claims 2-7.

Furthermore, applicants respectfully assert that the '838 patent (Liu et al.) does not disclose, expressly or inherently, the additional limitations of claims 2-6.

Claims 2, 4, and 6 of the Applicants' invention include a static grating as an additional limitation. The Examiner identifies the stacked waveplates 400 in Fig. 3a of the '838 patent (col. 4, lines 60-64, the '838 patent) with the static grating in the Applicants claimed invention. The stacked waveplates 400 in Fig. 3a of the '838 patent rotates by 90 degrees the initially horizontal polarization of the add signal 701 as it passes through the first stacked waveplates element 400 (col. 5, lines 16-24, the '838 patent). As seen in Fig. 3a of the '838 patent, the direction of propagation of the add signal is unchanged in passing through the first stacked waveplates element 400. In contrast, in the static grating in the Applicants' claimed invention, as in any grating, the direction of propagation of the output beam (or beams) deviates from the direction of the incoming beam. Therefore, the Applicants respectfully submit that the '838 patent does not teach or disclose, explicitly or implicitly, a static grating as claimed in claims 2, 4, and 6 of the Applicants' invention.

Claims 4 and 5 of the Applicant's invention include the additional limitation that the switchable diffraction gratings comprise switchable volume diffraction gratings, one switchable volume diffraction grating in claim 4 and two switchable volume diffraction gratings in claim 5. The Examiner identifies the second set of polarization rotators 302_1,

302_2 (col. 5, lines 40-51, the '838 patent) of the '838 patent as the one switchable volume diffraction grating and the third set of polarization rotators 303_1, 303_2 (col. 6, lines 12-25, the '838 patent) of the '838 patent as the two switchable volume diffraction gratings. As explained above, comparing the polarization rotators 302_1, 302_2 or, 303_1, 30-2 in Fig. 3a of the '838 patent to a volume diffraction grating as in claims 4 or 5 of the Applicants' invention, each polarization rotator "produces a new beam, coaxial with the incident beam, having a specified new polarization angle" while in each diffraction grating the direction of propagation of the output beam (or beams) deviates from the direction of propagation of the incoming beam. Furthermore, in a volume diffraction grating, if the thickness of the grating satisfies a known criterion (thick gratings), "although light is diffracted at angles according to the classical diffraction equations, the energy distribution of the diffracted light is given by Bragg diffraction" (see, for example, S. C. Barden et al., Evaluation Of Volume Phase Holographic Grating Technology, presented on August 2, 2001 at the SPIE International Symposium On Optical Science And Technology, a copy of which is attached in the appendix). No such relationship exists for polarization rotators. Applicants respectfully submit that the polarization rotators 302_1, 302_2 or 303_1,303_2 in Fig. 3a of the '838 patent are not volume diffraction gratings. Therefore, the Applicants respectfully submit that the '838 patent does not teach or disclose, explicitly or implicitly, volume diffraction gratings as claimed in claims 4 and 5 of the Applicants' invention.

Regarding claim 8, the provided optical system in the Applicants' claimed invention includes at least one switchable volume diffraction grating and a static grating.
By the arguments presented above, since the system of Fig. 3a of the '838 patent does not include a static grating or a switchable volume diffraction grating, Applicants respectfully assert that the '838 patent (Liu et el.) does not disclose, expressly or inherently, at least one patentable limitation (element) of claim 8.

Since claims 9 and 10 are dependent on claim 8, Applicants respectfully assert that the '838 patent (Liu et al.) does not disclose, expressly or inherently, at least one patentable limitation (element) of claims 9 or 10.

To anticipate a claim a reference must teach every element of the claim. (MPEP §2131). "A claim is anticipated only if each and every element as set forth in the claim is found, either expressly or inherently described, in a single prior art reference." *Verdegaal Bros. v. Union Oil Co. of California*, 814 F.2d 628, 631, 2 USPQ2d 1051, 1053 (Fed. Cir. 1987). As described, the '838 patent does not disclose, expressly or inherently, a polarization separating sub-system capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization, at least one switchable diffraction grating , means for varying a diffraction efficiency of said at least one switchable diffraction grating or a polarization recombining sub-system capable of capable of recombining the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization into at least one final output beam of combined polarization, or a static grating or a switchable volume diffraction grating, and, thus, the '838 patent does not anticipate the Applicants' claimed invention of claims 1-10.

Applicants respectfully assert that independent Claims 1 and 8 are not anticipated by the '838 patent and neither are any of the dependent claims. In addition, in view of the specific needs of the '838 patent (as discussed above) and since the '838 patent is lacking at least one patentable feature present in independent Claims 1, 8, and the dependent claims of the Applicants' invention, a modification of the '838 patent under 35 U.S.C. §103 would also be inapplicable because such modifications are not taught by nor obvious under the '838 patent, and if incorporated into the '838 patent, would render the '838 patent unsuitable for its intended functions.

In conclusion, in view of the above remarks, Applicants respectfully request the Examiner find claims, 1-10 as amended allowable over the prior art and pass this case to issue.

Since the total number of claims is less than the number of claims already been paid for, no additional fees are required. However, if fees are required, they should be charged to Deposit Account No. 50-1078.

In accordance with Section 714.01 of the MPEP, the following information is presented in the event that a call may be deemed desirable by the Examiner:

JACOB N. ERLICH (617) 854-4000.

Respectfully submitted,
Thomas W. Stone et al., Applicants

Dated: July 6, 2005

By:
Jacob N. Erlich
Reg. No. 24,338
Attorney for Applicants

ideal polarization rotator

See PREVIOUS | NEXT term in listing

Definition:

A theoretical instrument conceived of as a box that receives a beam of radiation of any arbitrary polarization angle and produces a new beam, coaxial with the incident beam, having a specified new polarization angle.

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we make light work.

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Polarization Rotators

The Polarization Rotator is the basis of all Displaytech Photonics products. Rotators are used to quickly and accurately modulate the polarization state of an incoming light beam. Our devices are electro-optical so they elicit an optical response with an electrical output.

Polarization Rotators, used in research and product development, are suited for optical switching, polarimetry, and image enhancement (microscopy).

The rotator works as an electrically switchable half-wave plate. This electro-optic component converts one state of optical polarization into the orthogonal states (rotates linearly polarized light 90). The cell is activated with a 5-volt pulse. Reversing the polarity controls the state of the cell.

The Polarization Rotators are centered for operation in the visible spectrum. Rotators are available in two wavelength options:

- a set centered wavelength of 510 nm
- customized wavelengths ranging from 400 nm - 1500 nm

The centerline is 510 nm with a retardance of 255 nm. The device yields as an exact halfwave response in green (510nm), slightly more than halfwave in blue (450nm), and less than a halfwave in red (650nm). The resulting spectral roll-off on both sides of the optimized wavelength causes chromatic or phase aberrations in broadband imaging applications.

To meet your optical flatness requirements, Polarization Rotators offers four size options in circular apertures in two types of black anodized aluminum housings:

- 13mm - circular housing
- 25mm - circular or square housing
- 45mm - circular housing
- customized clear circular aperture sizes

Mounts

Displaytech also offers a standard mount accommodating both the Polarization Rotator circular and square housings. The square housing mates with the standard mount that accommodates an 8/32nd threaded post hole for optical bench mounting.

Product Name	Model Number	Clear Aperture	Outer Dimension
13mm circular rotator	LV1300-OEM	12.7mm	25.2mm
25.4mm circular rotator	LV2500-OEM	25.3mm	37.9mm

25mm square rotator	LV2525-SQ	25.4mm	43.2 x 41.2mm
45mm circular rotator	LV4500-OEM	45.0mm	65.0mm
Mount	MTS-2525		

For custom orders, e-mail sales@displaytech.com.

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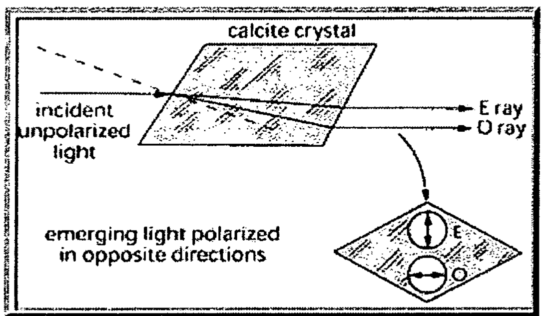
birefringence

Definition:

The separation of a light beam, as it penetrates a doubly refracting object, into two diverging beams, commonly known as ordinary and extraordinary beams.



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SECOND EDITION

EUGENE HECHT
Adelphi University

With Contributions by Alfred Zajac

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about it, following the motion of the crystal. The rays forming the fixed dot, which is the one invariably closer to the upper blunt corner, behave as if they had merely passed through a plate of glass. In accord with a suggestion made by Bartholinus, they are known as the **ordinary rays**, or *o-rays.* The rays coming from the other dot, which behave in such an unusual fashion, are known as the **extraordinary rays**, or *e-rays.* If the crystal is examined through an analyzer, it will be found that the ordinary and extraordinary images are linearly polarized (Fig. 8.21). Moreover, the two emerging $\mathcal{P}$-states are orthogonal.

Any number of planes can be drawn through the rhomb so as to contain the optic axis, and these are all called *principal planes.* More specifically, if the principal plane is also normal to a pair of opposite surfaces of the cleavage form, it slices the crystal across a *principal section.* There are evidently three of these passing through any one point; each is a parallelogram having angles of 109° and 71°. Figure 8.22 is a diagrammatic representation of an initially unpolarized beam traversing a principal section of a calcite rhomb. The filled-in circles and arrows drawn along the rays indicate that

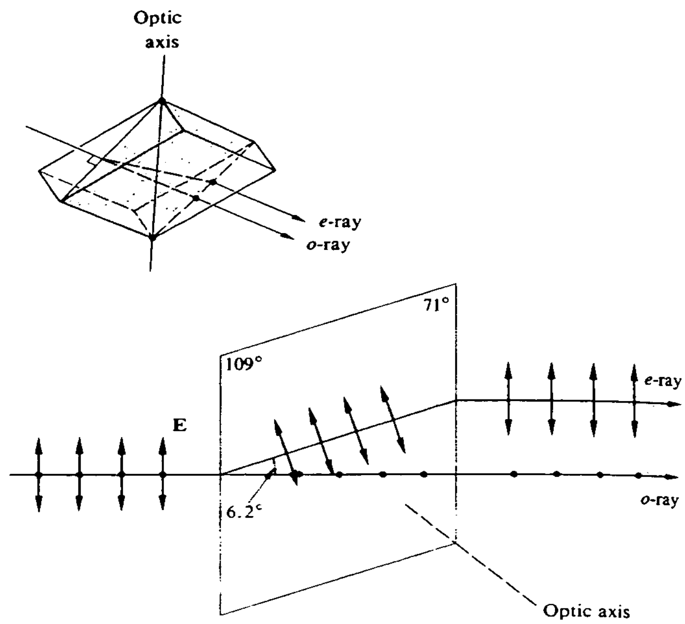

Figure 8.22 A light beam with two orthogonal field components traversing a calcite principal section.

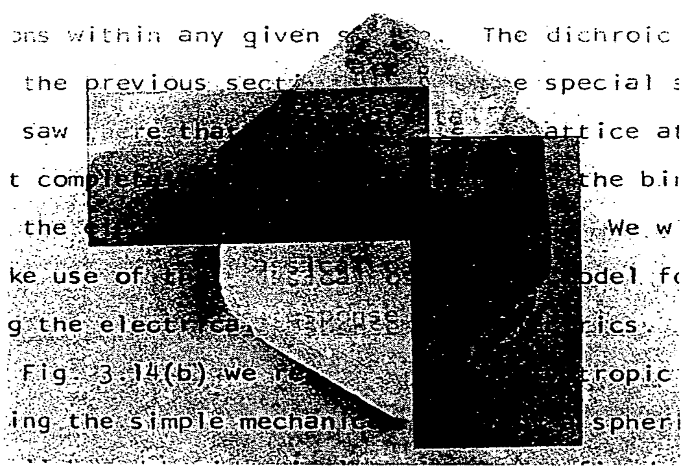

Figure 8.21 A calcite crystal (blunt corner on the bottom). The transmission axes of the two polarizers are parallel to their short edges. Where the image is doubled the lower, undeflected one is the ordinary image. Take a long look, there's a lot in this one. (Photo by E.H.)

the *o*-ray has its electric field vector normal to the principal section, and the field of the *e*-ray is parallel to the principal section.

To simplify matters a bit, let **E** in the incident plane wave be linearly polarized perpendicular to the optic axis, as shown in Fig. 8.23. The wave strikes the surface of the crystal, thereupon driving electrons into oscillation, and they in turn reradiate secondary wavelets. The wavelets superimpose and recombine to form the refracted wave, and the process is repeated over and over again until the wave emerges from the crystal. This represents a cogent physical argument for applying the ideas of Huygens's principle. Huygens himself, although without benefit of electromagnetic theory, used his construction to explain successfully many aspects of double refraction in calcite as long ago as 1690. It should be made clear from the outset, however, that his treatment is incomplete,* in which form it is appealingly, although deceptively, simple.

* A. Sommerfeld, *Optics,* p. 148.

8

See PREVIOUS | NEXT term in listing

wave plate

Definition:

An optical element having two principal axes, slow and fast, that resolve an incident polarized beam into two mutually perpendicular polarized beams. The emerging beam recombines to form a particular single polarized beam. Wave plates produce full-, half- and quarter- wave retardations. Also known as retardation plate.

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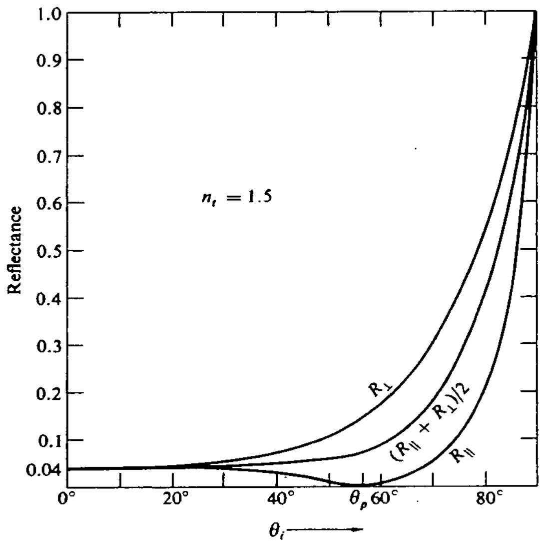

Figure 8.43 Reflectance versus incident angle.

orientation at which the transmitted irradiance is maximum (I_{max}), and perpendicular to this, a direction where it is minimum (I_{min}). Clearly $I_p = I_{max} - I_{min}$, and so

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}. \tag{8.30}$$

Note that V is actually a property of the beam, which may obviously be partially or even completely polarized before encountering any sort of polarizer.

8.7 RETARDERS

We shall now consider a class of optical elements known as **retarders**, which serve to change the polarization of an incident wave. In principle the operation of a retarder is quite simple. One of the two constituent coherent $\mathcal{P}$-states is somehow caused to lag in phase behind the other by a predetermined amount. Upon emerging from the retarder, the relative phase of the two components is different than it was initially, and thus the polarization state is different as well. Indeed, once we have developed the concept of the retarder, we will be able to convert any given polarization state into any other and in so doing create circular and elliptic polarizers as well.

8.7.1 Wave Plates and Rhombs

Recall that a plane monochromatic wave incident on a uniaxial crystal, such as calcite, is generally divided in two, emerging as an ordinary and an extraordinary beam. In contrast, we can cut and polish a calcite crystal so that its optic axis will be normal to both the front and back surfaces (Fig. 8.44). A normally incident plane wave can only have its **E**-field perpendicular to the optic axis. The secondary spherical and ellipsoidal wavelets will be tangent to each other in the direction of the optic axis. The o- and e-waves, which are envelopes of these wavelets, will be coincident, and a single undeflected plane wave will pass through the crystal; there are no relative phase shifts and no double images.*

Now suppose that the direction of the optic axis is arranged to be parallel to the front and back surfaces, as shown in Fig. 8.45. If the **E**-field of an incident monochromatic plane wave has components parallel and perpendicular to the optic axis, two separate plane waves will propagate through the crystal. Since $v_\parallel > v_\perp$, $n_o > n_e$, and the e-wave will move across the specimen more rapidly than the o-wave. After traversing a plate of thickness d the resultant electromagnetic wave is the superposition of the e- and o-waves, which now have a relative phase difference of $\Delta\varphi$. Keep in mind that these are harmonic waves of the same frequency whose **E**-fields are orthogonal. The relative optical path-length difference is given by

$$\Lambda = d(|n_o - n_e|), \tag{8.31}$$

and since $\Delta\varphi = k_0\Lambda$,

$$\Delta\varphi = \frac{2\pi}{\lambda_0} d(|n_o - n_e|), \tag{8.32}$$

* If you have a calcite rhomb, find the blunt corner and orient the crystal until you are looking along the direction of the optic axis through one of the faces. The two images will converge until they completely overlap.

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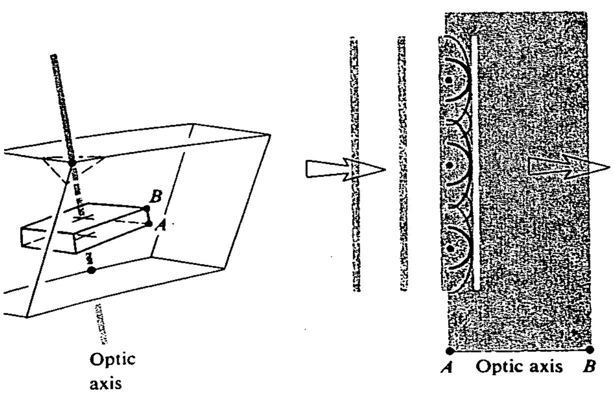


e 8.44 A calcite plate cut perpendicular to the optic axis.

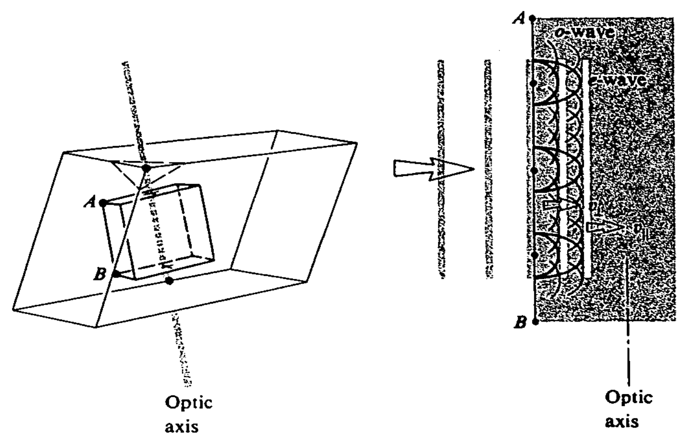


Figure 8.45 A calcite plate cut parallel to the optic axis.

re λ_0, as always, is the wavelength in vacuum (the ı containing the absolute value of the index ·rence is the most general statement). The state of rization of the emergent light evidently depends he amplitudes of the incoming orthogonal field ponents and of course on $\Delta\varphi$.

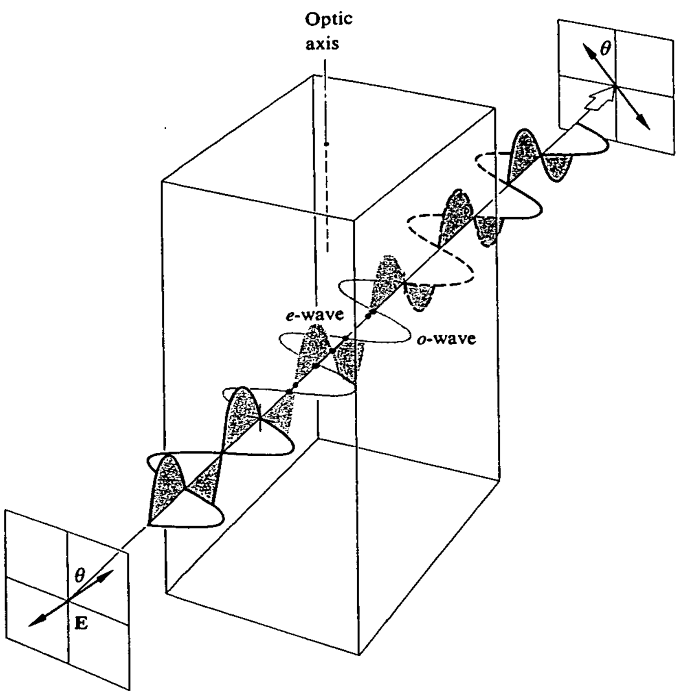
Full-Wave Plate

φ is equal to 2π, the *relative retardation* is one elength; the *e*- and *o*-waves are back in phase, and e is no observable effect on the polarization of the dent monochromatic beam. When the *relative dation* $\Delta\varphi$, which is also known as the *retardance*, is the device is called a *full-wave plate*. (This does not n that $d = \lambda$.) In general the quantity $|n_o - n_e|$ in (8.32) changes little over the optical range, so that varies effectively as $1/\lambda_0$. Evidently a full-wave plate function only in the manner discussed for a par- lar wavelength, and retarders of this sort are thus to be *chromatic*. If such a device is placed at some trary orientation between crossed linear polarizers, he light entering it (in this case let it be white light) be linear. Only the one wavelength that satisfies Eq. 2) will pass through the retarder unaffected, reafter to be absorbed in the analyzer. All other elengths will undergo some retardance and will ordingly emerge from the wave plate as various forms of elliptical light. Some portion of this light will proceed through the analyzer, finally emerging as the complementary color to that which was extinguished. It is a common error to assume that a full-wave plate behaves as if it were isotropic at all frequencies; it obviously doesn't.

Recall that in calcite, the wave whose **E**-field vibrations are parallel to the optic axis travels fastest, that is, $v_\parallel > v_\perp$. The direction of the optic axis in a *negative* uniaxial retarder is therefore often referred to as the **fast axis,** and the direction perpendicular to it is the **slow axis.** For *positive* uniaxial crystals, such as quartz, these principal axes are reversed, with the slow axis corresponding to the optic axis.

The Half-Wave Plate

A retardation plate that introduces a relative phase difference of π radians or 180° between the *o*- and *e*-waves is known as a *half-wave plate.* Suppose that the plane of vibration of an incoming beam of linear light makes some arbitrary angle θ with the fast axis, as shown in Fig. 8.46. In a negative material the *e*-wave will have a higher speed (same ν) and a longer wavelength than the *o*-wave. When the waves emerge from the plate there will be a relative phase shift of $\lambda_0/2$ (that is, $2\pi/2$ radians), with the effect that **E** will have rotated through 2θ. Going back to Fig. 8.7, it should be evident that a



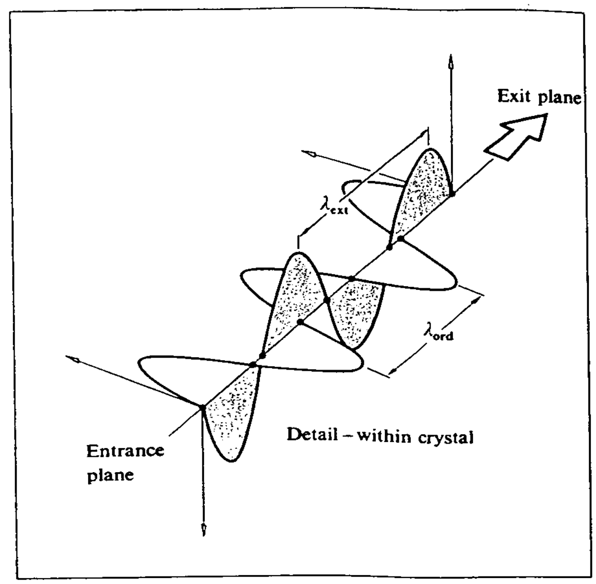


Figure 8.46 A half-wave plate.

half-wave plate will similarly flip elliptical light. In addition, it will invert the handedness of circular or elliptical light, changing right to left and vice versa.

As the e- and o-waves progress through any retardation plate, their relative phase difference $\Delta\varphi$ increases, and the state of polarization of the wave therefore gradually changes from one point in the plate to the next. Figure 8.7 can be envisioned as a sampling of a few of these states at one instant in time taken at different locations. Evidently if the thickness of the material is such that

$$d(|n_o - n_e|) = (2m + 1)\lambda_0/2,$$

where $m = 0, 1, 2, \ldots$, it will function as a half-wave plate ($\Delta\varphi = \pi, 3\pi, 5\pi$, etc.).

Although its behavior is simple to visualize, calcite is actually not often used to make retardation plates. It is quite brittle and difficult to handle in thin slices, but more than that, its birefringence, the difference between n_e and n_o, is a bit too large for convenience. On the other hand, quartz with its much smaller birefringence is frequently used, but it has no natural cleavage planes and must be cut, ground, and polished, making it rather expensive. The biaxial crystal mica is used most often. There are several forms of mica that serve the purpose admirably, for example, fluophlogopite, biotite, or muscovite. The most commonly occurring variety is the pale brown muscovite. It is very easily cleaved into strong, flexible, and exceedingly thin large-area sections. Moreover, its two principal axes are almost exactly parallel to the cleavage planes. Along those axes the indices are about 1.599 and 1.594 for sodium light, and although these numbers vary slightly from one sample to the next, their difference is fairly constant. The minimum thickness of a mica half-wave plate is about 60 microns. Crystalline quartz, single crystal magnesium fluoride (for the IR range from 3000 nm to about 6000 nm), and cadmium sulfide (for the IR range from 6000 nm to about 12,000 nm) are also widely used for wave plates.

Retarders are also made from sheets of polyvinyl alcohol that have been stretched so as to align their long-chain organic molecules. Because of the evident

isotropy, electrons in the material do not experience e same binding forces along and perpendicular to the rection of these molecules. Substances of this sort are erefore permanently birefringent, even though they e not crystalline.

You can make a rather nice half-wave plate by just aching a strip of ordinary (glossy) cellophane tape er the surface of a microscope slide. The fast axis, at is, the vibration direction of the faster of the two ves, corresponds to the transverse direction across tape's width, and the slow axis is along its length. ring its manufacture, cellophane (which is made m regenerated cellulose extracted from cotton or od pulp) is formed into sheets, and in the process its lecules become aligned, leaving it birefringent. If u put your half-wave plate between crossed linear larizers, it will show no effect when its principal axes ncide with those of the polarizers. If, however, it is at 45° with respect to the polarizer, the **E**-field erging from the tape will be flipped 90° and will thus parallel to the transmission axis of the analyzer. Light l pass through the region covered by the tape as if ere a hole cut in the black background of the crossed arizers (Fig. 8.47). A piece of cellophane wrapping ., from certain cigarette packs) will generally also ction as a half-wave plate. See if you can determine orientation of each of its principal axes using the e retarder and crossed polaroids. (Notice the fine allel ridges on the sheet cellophane.)

Quarter-Wave Plate

e quarter-wave plate is an optical element that intro-es a relative phase shift of $\Delta\varphi = \pi/2$ between the stituent orthogonal *o*- and *e*-components of a wave. ollows once again from Fig. 8.7 that a phase shift of will convert linear to elliptical light and vice versa. hould be apparent that linear light incident parallel ither principal axis will be unaffected by any sort of rdation plate. You can't have a *relative* phase erence without having two components. With dent *natural* light, the two constituent $\mathscr{P}$-states are herent, that is, their relative phase difference nges randomly and rapidly. The introduction of an itional constant phase shift by any form of retarder

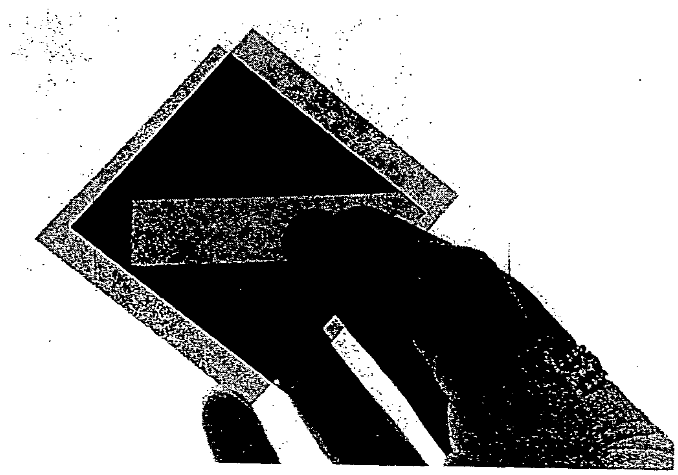


Figure 8.47 A hand holding a piece of Scotch tape stuck to a microscope slide between two crossed polaroids. (Photo by E.H.)

will still result in a random phase difference and thus have no noticeable effect. When linear light at 45° to either principal axis is incident on a quarter-wave plate, its *o*- and *e*-components have equal amplitudes. Under these special circumstances a 90° phase shift converts the wave into circular light. Similarly, an incoming circular beam will emerge linearly polarized.

Quarter-wave plates are also usually made of quartz, mica, or organic polymeric plastic. In any case, the thickness of the birefringent material must satisfy the expression $d(|n_o - n_e|) = (4m + 1)\lambda_0/4$. You can make a crude quarter-wave plate using household plastic food wrap, the thin stretchy stuff that comes on rolls. Like cellophane, it has ridges running in the long direction, which coincides with a principal axis. Overlap about a half dozen layers, being careful to keep the ridges parallel. Position the plastic at 45° to the axes of a polarizer and examine it through a rotating analyzer. Keep adding one layer at a time until the irradiance stays roughly constant as the analyzer turns; at that point you will have circular light and a quarter-wave plate. This is easier said than done in white light, but it's well worth trying.

Commercial wave plates are generally designated by their *linear retardation*, which might be, for example, 140 nm for a quarter-wave plate. This simply means

that the device has a 90° retardance only for green light of wavelength 560 nm (i.e., 4 × 140). The linear retardation is usually not given quite that precisely; 140 ± 20 nm is more realistic. The retardation of a wave plate can be increased or decreased from its specified value by tilting it somewhat. If the plate is rotated about its fast axis, the retardation will increase, whereas a rotation about the slow axis has the opposite effect. In this way a wave plate can be tuned to a specific frequency in a region about its nominal value.

The Fresnel Rhomb

We saw in Chapter 4 that the process of total internal reflection introduced a relative phase difference between the two orthogonal field components. In other words, the components parallel and perpendicular to the plane of incidence were shifted in phase with respect to each other. In glass ($n = 1.51$) a shift of 45° accompanies internal reflection at the particular incident angle of 54.6° [Fig. 4.25(e)]. The Fresnel rhomb shown in Fig. 8.48 utilizes this effect by causing the beam to be internally reflected twice, thereby imparting a 90° relative phase shift to its components. If the incoming plane wave is linearly polarized at 45° to the plane of incidence, the field components $[E_i]_{\parallel}$ and $[E_i]_{\perp}$ will

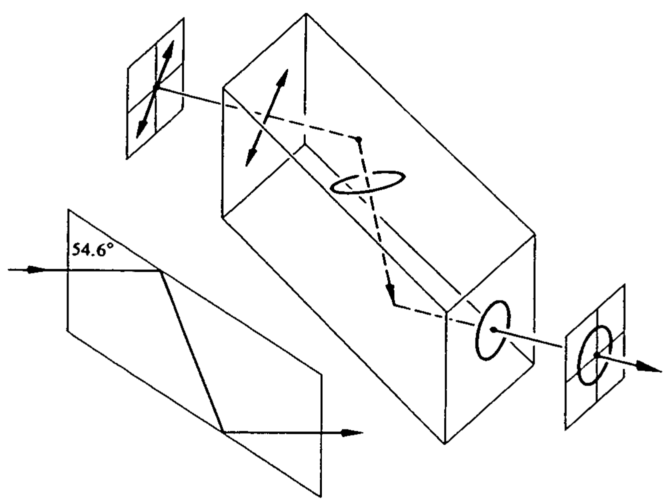


Figure 8.48 The Fresnel rhomb.

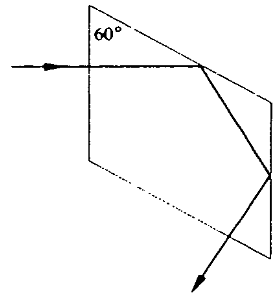
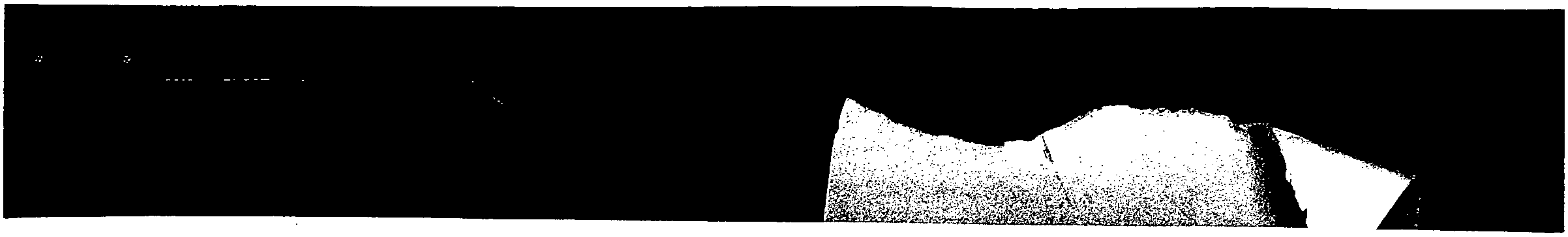


Figure 8.49 The Mooney rhomb.

initially be equal. After the first reflection the wave within the glass will be elliptically polarized. After the second reflection it will be circular. Since the retardance is almost independent of frequency over a large range, the rhomb is essentially an *achromatic* 90° retarder. The Mooney rhomb ($n = 1.65$) shown in Fig. 8.49 is similar in principle, although its operating characteristics are different in some respects.

8.7.2 Compensators

A compensator is an optical device that is capable of impressing a controllable retardance on a wave. Unlike a wave plate where $\Delta\varphi$ is fixed, the relative phase difference arising from a compensator can be varied continuously. Of the many different kinds of compensators, we shall consider only two of those that are used most widely. The Babinet compensator, depicted in Fig. 8.50, consists of two independent calcite, or more commonly quartz, wedges whose optic axes are indicated by the lines and dots in the figure. A ray passing vertically downward through the device at some arbitrary point will traverse a thickness of d_1 in the upper wedge and d_2 in the lower one. The relative phase difference imparted to the wave by the first crystal is $2\pi d_1(|n_o - n_e|)/\lambda_0$, and that of the second crystal is $-2\pi d_2(|n_o - n_e|)/\lambda_0$. As in the Wollaston prism, which this system closely resembles but which has larger angles and is much thicker, the o- and e-rays in the upper wedge become the e- and o-rays, respectively, in the bottom wedge. The compensator is thin (the wedge angle is typically about 2.5°), and thus the



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10

10 DIFFRACTION

10.1 PRELIMINARY CONSIDERATIONS

An opaque body placed midway between a screen and a point source casts an intricate shadow made up of bright and dark regions quite unlike anything one might expect from the tenets of geometrical optics (Fig. 10.1).* The work of Francesco Grimaldi in the 1600s was the first published detailed study of this *deviation of light from rectilinear propagation,* something he called "*diffractio.*" *The effect is a general characteristic of wave phenomena occurring whenever a portion of a wavefront, be it sound, a matter wave, or light, is obstructed in some way.* If in the course of encountering an obstacle, either transparent or opaque, a region of the wavefront is altered in amplitude or phase, diffraction will occur.† The various segments of the wavefront that propagate beyond the obstacle interfere, causing the particular energy-density distribution referred to as the diffraction pattern. There is no significant physical distinction between *interference* and *diffraction.* It has, however, become somewhat customary, if not always appropriate, to speak of interference when considering the superposition of only a few waves and diffraction when treating a large number of waves. Even so, one refers to multiple-beam interference in one context and diffraction from a grating in another.

We might mention parenthetically that the wave

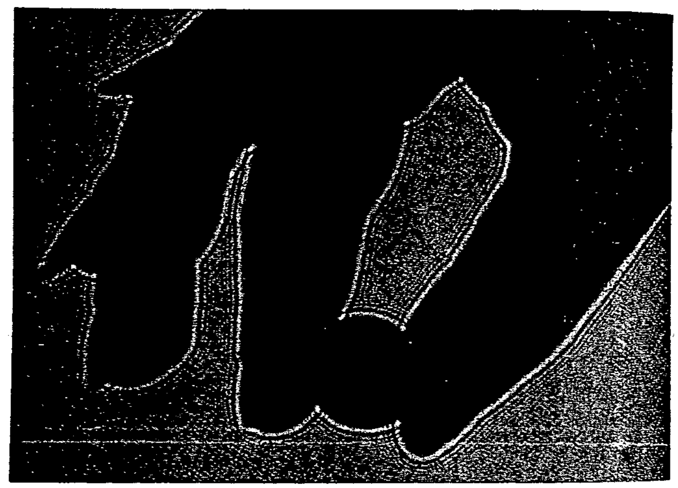
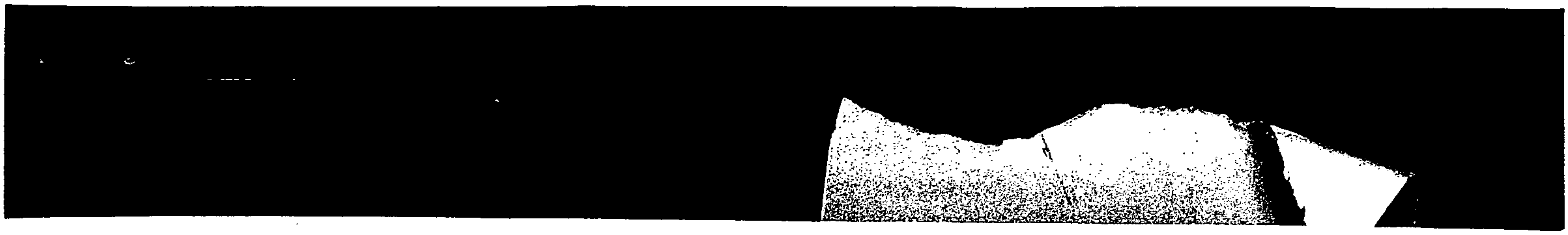


Figure 10.1 The shadow of a hand holding a dime, cast directly on 4 × 5 Polaroid A.S.A. 3000 film using a He–Ne beam and no lenses. (Photo by E.H.)

* The effect is easily seen, but you need a fairly strong source. A high-intensity lamp shining through a small hole works well. If you look at the shadow pattern arising from a pencil under point-source illumination, you will see an unusual bright region bordering the edge and even a faintly illuminated band down the middle of the shadow. Take a close look at the shadow cast by your hand in direct sunlight.

† Diffraction associated with transparent obstacles is not usually considered, although if you have ever driven an automobile at night with a few rain droplets on your eyeglasses, you are no doubt quite familiar with the effect. If you have not, put a droplet of water or saliva on a glass plate, hold it very close to your eye, and look directly through it at a point source. You'll see bright and dark fringes.



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maximum has a broad flat top; in other words, at the origin, which is the center of the peak, the second derivative of the irradiance function is zero; there is no change in slope (Fig. 10.40).

Unlike the Rayleigh rule, which rather tacitly assumes incoherence, the Sparrow condition can readily be generalized to coherent sources. In addition, astronomical studies of equal-brightness stars have shown that Sparrow's criterion is by far the more realistic.

10.2.7 The Diffraction Grating

A repetitive array of diffracting elements, either apertures or obstacles, that has the effect of producing periodic alterations in the phase, amplitude, or both of an emergent wave is said to be a **diffraction grating**. One of the simplest such arrangements is the multiple-slit configuration of Section 10.2.3. It seems to have been invented by the American astronomer David Rittenhouse in about 1785. Some years later Joseph von Fraunhofer independently rediscovered the principle and went on to make a number of important contributions to both the theory and technology of gratings. The earliest devices were indeed multiple-slit assemblies, usually consisting of a grid of fine wire or thread wound about and extending between two parallel screws, which served as spacers. A wavefront, in passing through such a system, is confronted by alternate opaque and transparent regions, so that it undergoes a modulation in *amplitude*. Accordingly, a multiple-slit configuration is said to be a *transmission amplitude grating*. Another, more common form of transmission grating is made by ruling or scratching parallel notches into the surface of a flat, clear glass plate [Fig. 10.34(a)]. Each of the scratches serves as a source of scattered light, and together they form a regular array of parallel line sources. When the grating is totally transparent, so that there is negligible amplitude modulation, the regular variations in the optical thickness across the grating yield a modulation in *phase*, and we have what is known as a *transmission phase grating* (Fig. 10.35). In the Huygens–Fresnel representation you can envision the wavelets as radiated with different phases over the grating surface. An emerging wavefront therefore contains periodic variations in its shape rather than its amplitude. This in turn is equivalent to an angular distribution of constituent plane waves.

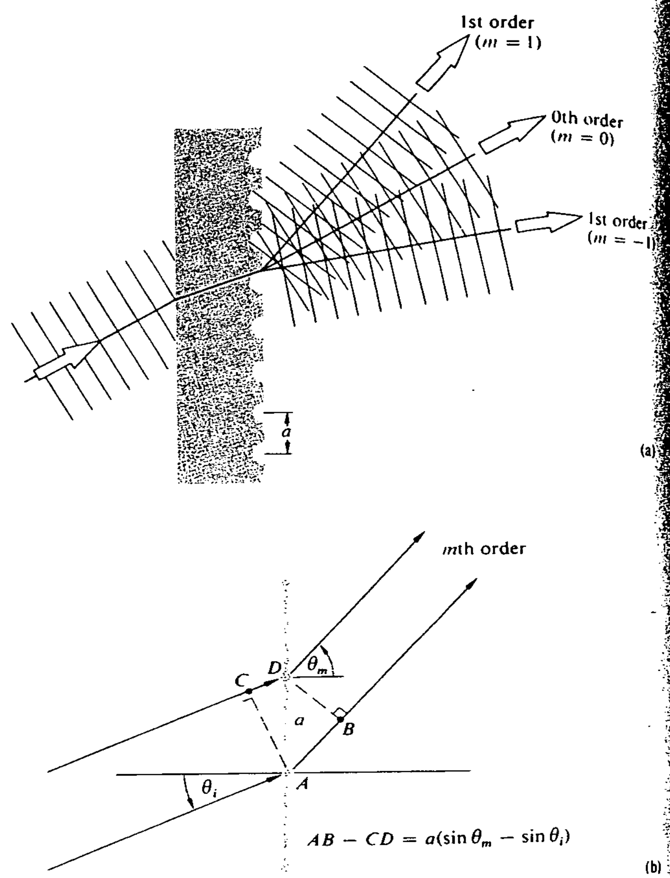

Figure 10.34 A transmission grating.

On reflection from this kind of grating, light scattered by the various periodic surface features will arrive at some point P with a definite phase relationship. The consequent interference pattern generated after reflection is quite similar to that arising from transmission. Gratings designed specifically to function in this fashion are known as *reflection phase gratings* (Fig. 10.36). Contemporary gratings of this sort are generally ruled in thin films of aluminum that have been evaporated onto optically flat glass blanks. The aluminum, being fairly

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Evaluation of volume-phase holographic grating technology

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Evaluation of volume-phase holographic grating technology

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ABSTRACT

An overview of the measured performance for a variety of volume-phase holographic (VPH) gratings is presented. Many of the gratings analyzed were developed as part of a National Science Foundation funded effort to explore the viability of this technology for astronomical applications. Additional emphasis is given to some remaining issues with this technology and the likely means to resolve them.

Keywords: diffraction gratings, spectrographs, instruments, astronomical spectrographs

1. INTRODUCTION

Volume-phase holographic (VPH) gratings show great promise as a viable dispersing element for use in astronomical spectrographs[1,2]. Their behavior as Bragg gratings, due to diffraction arising from sinusoidal-like modulations in the refractive index of the material, gives them properties and efficiency performance characteristics unavailable with either diamond ruled or holographically generated, classical surface-relief (SR) diffraction gratings.

Previous papers have covered many of the fundamentals and performance characteristics of VPH gratings with regard to astronomical applications[1,2]. The current paper will review and expand upon that set of knowledge. In particular, we will show measured efficiency curves for some types of VPH gratings that were not covered in the previously published set of papers and discuss some remaining issues regarding VPH grating performance.

2. OVERVIEW OF VPH GRATING PHYSICS

VPH gratings diffract light by a fringe structure due to modulations in the refractive index of the grating material. Although light is diffracted at angles according to the classical diffraction equation, the energy distribution of the diffracted light is controlled by Bragg diffraction. The angle of incidence, the grating depth, and the intensity of the index modulation all interact to determine the energy profile of the diffracted light as a function of wavelength[3]. A change in the angle of incidence results in a shift of the energy distribution allowing the gratings to be somewhat tunable. Grating fringe structures range from transmissive-Littrow gratings with fringes normal to the grating surface, to reflective gratings in which the fringes are nearly parallel to the grating surface.

Rigorous coupled wave analysis[4, 5] (RCWA) is typically required to properly model the expected performance of a VPH grating. Approximation theories can also provide viable descriptions of VPH gratings under certain configurations and assumptions[3].

A typical VPH grating is made from Dichromated Gelatin (DCG). DCG is capable of a relatively wide range of index modulations from 0.02 to 0.10 while retaining good clarity and low scattering over a broad span of wavelengths (from 300 nm to at least 1800 nm and possibly up to 2800 nm). Typical grating depths range from a few microns to greater than 20 μm. DCG is also capable of recording fringe structure ranging from about 300 to 6000 lines per mm.

The hygroscopic nature of DCG typically requires that the grating be encapsulated and the grating must never exceed a temperature of 200 C. Encapsulation allows the use of anti-reflective coatings on the outer surfaces of the substrate and cover materials to further enhance the efficiency of a VPH grating. Unlike SR gratings, VPH gratings are protected from dirt and can be handled more like a band-pass filter rather than a conventional grating. If properly encapsulated and handled, the performance of a VPH grating should remain stable for a period of at least 20 years.

3. MEASURED PERFORMANCE OF VPH GRATINGS

The gratings measured and presented here include the following:

- 300 l/mm transmissive grating
- 1200 l/mm transmissive grating
- 2400 l/mm transmissive grating
- a multiplex grating containing both 1200 and 1620 l/mm transmissive gratings
- 1200 l/mm reflective grating
- 300 l/mm transmissive, high order grating
- 4800 l/mm transmissive grating with prism substrates
- 450 l/mm transmissive grism

1. 300 l/mm transmissive grating

The 300 l/mm transmissive grating was fabricated to have optimal performance at 1064 nm with a diffraction angle of 9 degrees. Figure 1 displays the measured efficiency for this grating at the nominal 9-degree angle of incidence along with efficiencies at 6 and 12 degrees. Note that the efficiency envelope shifts and actually allows higher order diffraction as the grating angle is increased.

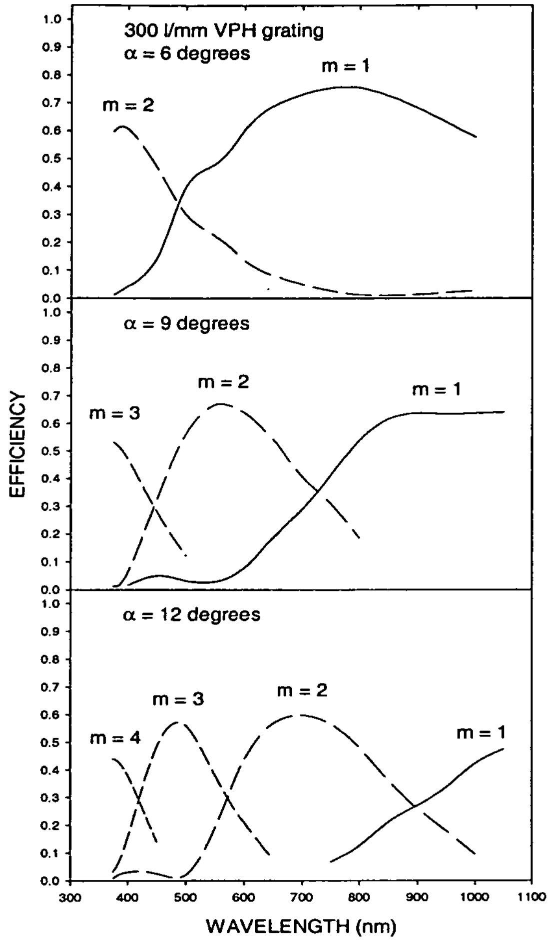

Figure 1 Measured efficiency of the 300 l/mm VPH grating in unpolarized light at three different grating angles.

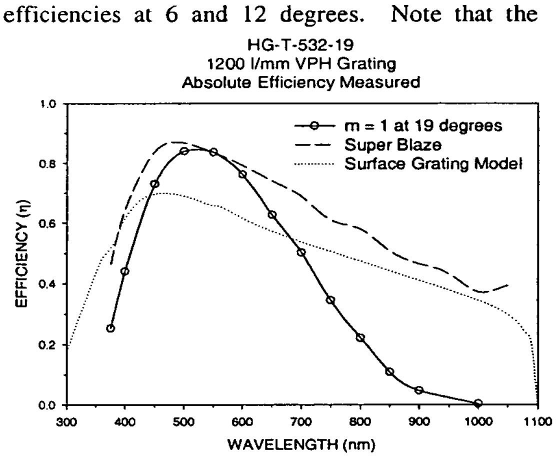

Figure 2 Measured efficiency of the 1200 l/mm grating.

2. 1200 l/mm transmissive grating

Figure 2 shows the measured total efficiency of the 1200 l/mm grating. This grating was designed for optimal performance at 19 degrees with peak efficiency at 532 nm. In addition to the efficiency envelope for the grating at 19 degrees, the superblaze for the grating is also shown. The superblaze is the envelope that traces the peak efficiency of the grating as the grating angle is varied. Note that the superblaze is comparable in shape to the blaze profile of a 1200 l/mm SR

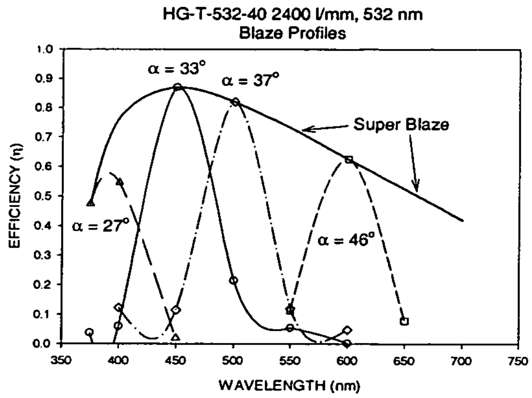

Figure 3 Measured efficiency for the 2400 l/mm grating.

grating (shown in the figure for comparison). Also note that the overall peak efficiency of the VPH grating exceeds that of the SR grating.

3. 2400 l/mm transmissive grating

The efficiency measured for the 2400 l/mm grating is displayed in Figure 3. The "blaze" profiles for the grating at 27, 33, 37, and 46 degrees are given along with a plot of the superblaze. This particular grating was designed to have optimal performance at a grating angle of 40 degrees with peak efficiency at 532 nm. This grating actually performs much better when tuned blueward, or to lower angles of incidence, than at its nominal design wavelength. The overall peak efficiency of this grating, including substrate losses, is about 88% at 33 degrees at 450 nm.

4. 1200/1620 multiplex transmissive grating

One advantage of VPH grating technology is the ability to stack multiple gratings into a single grating assembly and to have those gratings perform in a manner that typical SR gratings can not. The multiplex grating described here was fabricated to simultaneously diffract the light of Hydrogen alpha (656 nm) and Hydrogen beta (486 nm) at the same angle of diffraction. This can be done by stacking two gratings on top of each other. The 1200 l/mm grating is designed for optimal efficiency at 656 nm when tuned to an incident angle of 23 degrees. The bandwidth of the grating is targeted to make the grating have nearly zero diffraction efficiency for the wavelength of 486 nm at that angle of use. Hence, the grating would effectively be invisible to the light of H-beta. The 1620 l/mm grating is designed to do the opposite. That is, it has optimal efficiency diffracting 486 nm light at an angle of 23 degrees while the bandwidth is set to minimize diffraction of the 656 nm light. This makes the 1620 l/mm grating invisible to the light of H-alpha. The gratings are then slightly rotated about the axis perpendicular to the grating surface with respect to each other to cause the spectra from each to diverge and be separate from each other when imaged on to a detector.

Figure 4 displays the measured efficiency of each grating in this assembly. Shown are representative efficiency profiles for 17, 23, and 33 degrees as well as the superblaze for each grating. Also shown is the RCWA predicted superblaze. Although the 1200 l/mm grating superblaze tracks the predicted curve and actually exceeds it in efficiency, the produced bandwidth of the grating is too narrow. At 23 degrees the

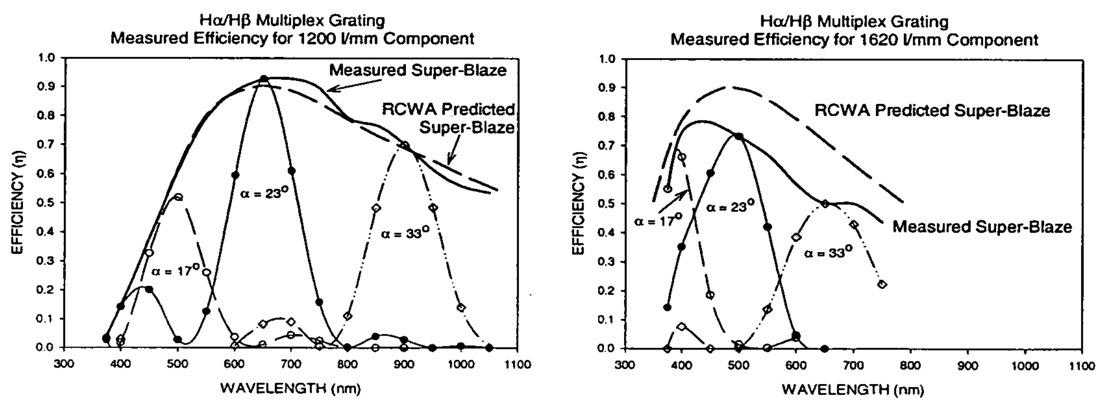

Figure 4 Measured efficiency for both grating components of the multiplex grating.

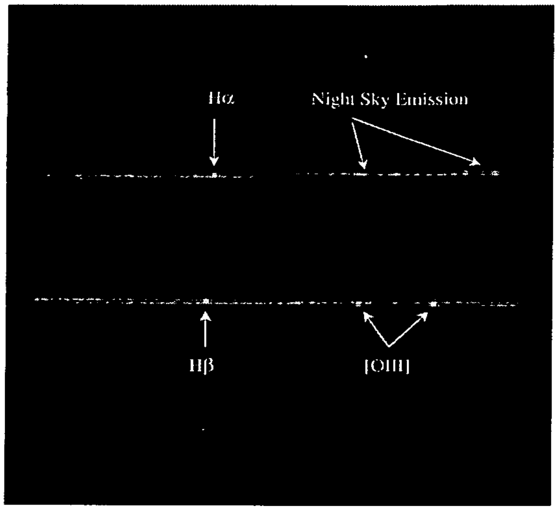

Figure 5 Spectra as imaged onto a detector with the multiplex grating.

minima between the main efficiency peak and the lower wavelength side lobe falls at about 510 nm rather than 486 nm. This results in about 15% of the light at 486 nm being diffracted by the 1200 l/mm grating. Hence, only 85% of the H-beta light gets diffracted by the 1620 l/mm grating and explains the discrepancy between the measured superblaze and that predicted for that grating. Regardless of this slight defect, this grating still shows superb efficiency performance with a peak efficiency of nearly 93% for the 1200 l/mm grating and a respectable peak efficiency of 80% for the 1620 l/mm grating.

Figure 5 shows how the resultant spectra are imaged on to a detector. The spectrum from the 1200 l/mm grating component angles slightly upward while that of the 1620 l/mm grating angles slightly downward. The two spectra cross each other at zeroth order.

5. 1200 l/mm reflective grating

As pointed out in section 2, the fringes of a VPH grating can be tilted with respect to the grating surface. This can either result in a transmissive grating with non-Littrow performance when the fringe tilt is not significant or a reflection grating when the fringe tilt is significant and more nearly parallel with the grating surface.

One potential advantage of a reflective VPH grating is the ability to "saturate" the diffraction efficiency. The diffraction efficiency of a transmissive VPH grating varies as a function of the square of the sine of the grating depth[3]. This means that the fabrication processes of the grating must hit a particular target of grating depth in order to achieve peak efficiency. If the grating ends up being either slightly too thick or too thin, the efficiency will be lower than desired. A reflective grating, on the other hand, diffracts light back out the same side that the light first entered. Thus, the light does not "see" the entire depth of the grating. The depth of the grating can then be increased without compromising, or risking, a decrease in diffraction efficiency. In fact, the efficiency of the grating will eventually saturate at 100%. This is shown in Figure 6, which is an RCWA prediction of the efficiency for a reflective grating with 1200 l/mm operating at 532 nm. Unfortunately, the bandwidth of reflective VPH gratings tend to be extremely narrow since the Bragg condition must be more precisely met for efficient diffraction than with transmissive VPH gratings. The undiffracted light continues to transmit through the grating material. Note the narrow bandwidth of the efficiency curve shown in Figure 6 and compare it to that displayed in Figure 2 for a 1200 l/mm transmissive VPH grating.

One way to enhance the bandwidth of a reflective VPH grating is to allow the index modulation to change as a function of grating depth. This results in a wavelength shift of the Bragg condition and shifts the diffraction efficiency in wavelength. If this is done correctly, the grating can function as an equivalent stack of gratings, each with a different wavelength of operation. The bandwidth can then be increased while maintaining a relatively high efficiency level. This approach was attempted in the fabrication of the 1200 l/mm reflective grating described here.

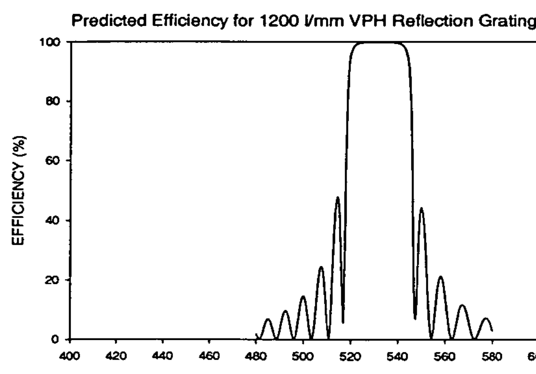

Figure 6 Theoretical efficiency curve for a saturated reflection grating.

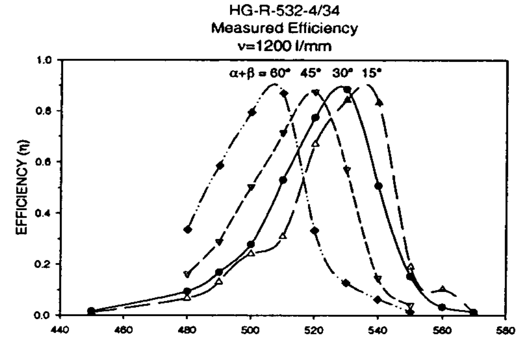

Figure 7 Measured efficiency of the 1200 l/mm reflection grating.

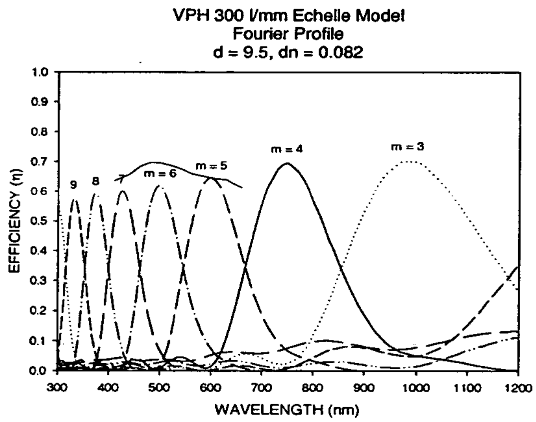

Figure 8 Theoretical efficiency of a high-order, 300 l/mm VPH grating with non-sinusoidal index modulation.

Figure 7 shows the measured efficiency of the 1200 l/mm reflective grating at 4 different angles (the angle between the angle of incidence and the angle of diffraction; equal to 15, 30, 45, and 60 degrees). Although the grating efficiency did not become saturated as hoped, it did gain some width. Also, note that the peak efficiency remains constant at 90%, but shifts in wavelength as the grating is tilted.

6. 300 l/mm high order transmissive grating

The evaluated behavior of the initial 300 l/mm grating (described above), which showed good diffraction efficiency in some higher orders of diffraction by tuning the grating, gives promise that VPH grating technology could produce a moderately high-order echellette-type grating. Classical RCWA analysis in which the fringe structure is assumed to be purely sinusoidal does not predict such good efficiency performance in the diffractive orders above m=1 or 2. However, a profile that is quasi-sinusoidal, with higher Fourier terms, can produce behavior similar to that seen in the first 300 l/mm grating. Assuming that the extra Fourier terms are introduced by non-linearity in the exposure of the fringes led to the attempt to make a high order grating.

The RCWA predicted efficiency of a high-order grating is shown in Figure 8 in which the index profile is similar to that given by Barden, Arns, Colburn, and Williams[2]. The grating is tuned to diffract light of 500 nm wavelength into the 6^{th} order of diffraction (diffraction angle of 26.7 degrees). The predicted superblaze for 5^{th} order is also shown for a grating angle ranging from 20 to 32 degrees.

The measured efficiency of the final grating is displayed in Figure 9. Only two wavelengths have been measured. The plots display the efficiency of the grating at 650 and 400 nm as a function of incident angle on the grating. Curves for a range of diffraction orders are shown (m=0 to 5 for 650 nm; m=0 to 7 for 400 nm). Comparison with Figure 8 suggests that the grating is not performing optimally. The efficiencies are, however, considerably higher than that achieved for the original 300 l/mm grating, especially in the higher orders of diffraction.

As far as we are aware, this has been the first actual attempt at fabricating a VPH echellette-like grating. Better control in the fringe structure is required before VPH gratings with performance at much higher diffraction orders can compete with classical SR echellette and echelle gratings.

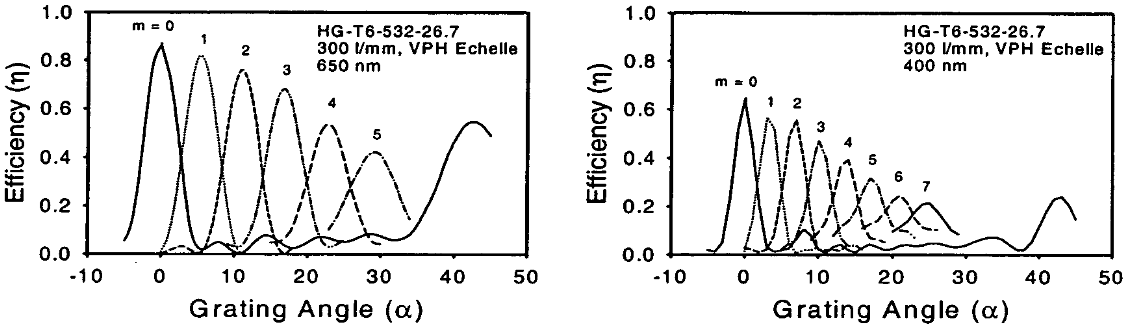

Figure 9 Measured efficiency of the high-order, 300 l/mm VPH grating at 650 and 400 nm as a function of grating tilt angle. The diffraction orders are labeled.

7. 4800 l/mm transmissive grating with prism substrates

Two very high frequency gratings were fabricated through the NSF effort: a 2400 l/mm grating at 1064 nm and a 4800 l/mm grating at a wavelength of 532 nm. Only the 4800 l/mm grating has been evaluated. Prism substrates are required for both of these gratings as the diffracted orders would be evanescent if the substrates were plane-parallel surfaces. Figure 10 gives a schematic representation of the grating assembly.

The measured efficiency of the 4800 l/mm grating is displayed in Figure 11 for two wavelengths as a function of grating angle. The angle of the grating is measured as if the grating substrates were plane-parallel. Note the extreme narrow bandpass for the grating.

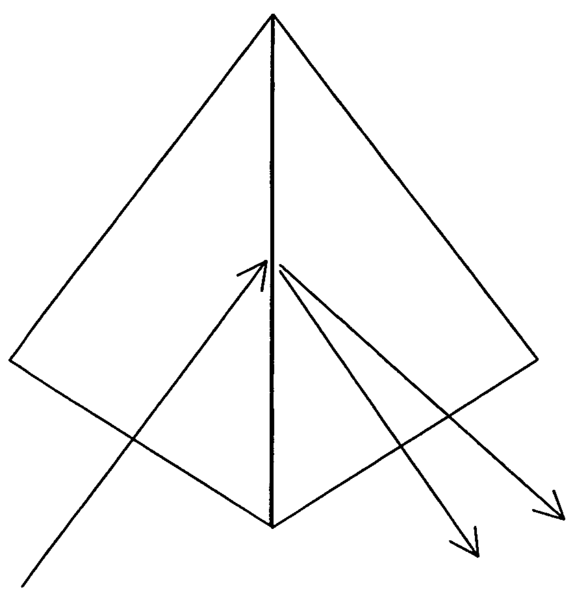

Figure 10 Schematic of a high line frequency grating with prism substrates.

8. 450 l/mm transmissive grism

As part of an upgrade project for an instrument at the Kitt Peak National Observatory, a 450 l/mm VPH grating was made and inserted between two prism wedges for use as a grism. The undeviated wavelength of the grating was targeted to be 805 nm. The grating is encased between a plate of BK7 glass and an OG550 longpass filter that serves as a blocker for 2nd order diffraction of the blue wavelengths. The BK7/OG550 assembly was then sandwiched between two SF11 glass wedges with a high performance AR coating on their outer surfaces.

The resultant grism assembly has a measured efficiency that almost perfectly matches the predicted efficiency based upon the original specifications for the grating. This is shown in Figure 12 which gives the efficiency of the measured assembly, the predicted performance, and the measured efficiency of a classical SR grism assembly with a 300 l/mm line frequency for comparison.

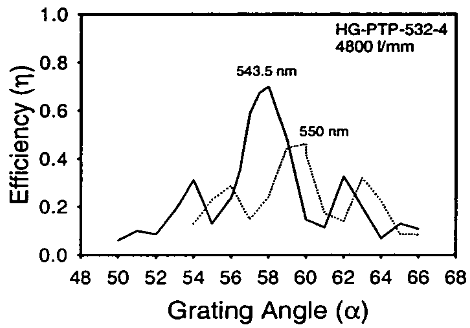

Figure 11 Measured efficiency of the 4800 l/mm VPH grating at two wavelengths as a function of grating angle.

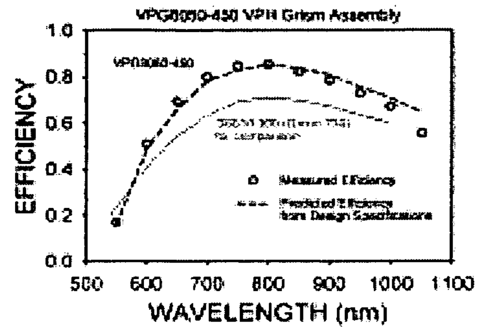

Figure 12 Measured efficiency of the 450 l/mm VPH grism assembly and comparison with the predicted efficiency and the measurements of a SR grism with 300 l/mm.

4. WAVEFRONT PERFORMANCE

The optical imaging performance of a grating can be as critical as its other aspects of performance, such as diffraction efficiency. Most astronomical spectrographs are rather forgiving in that the grating could have wavefront errors of on the order of one to maybe two waves. However, the increasing demand for diffraction limited instruments to be used with adaptive optics on ground-based telescopes and/or their use in space-based missions will require that diffraction gratings have ¼ wave or better performance.

One potential drawback to VPH grating technology is the need to mount the grating between two plates of glass. If the plates are too thin it can become difficult to generate a high level of imaging performance. The act of cementing such plates together can seriously distort the surfaces of the assembly resulting in a drastic degradation of the overall imaging capability.

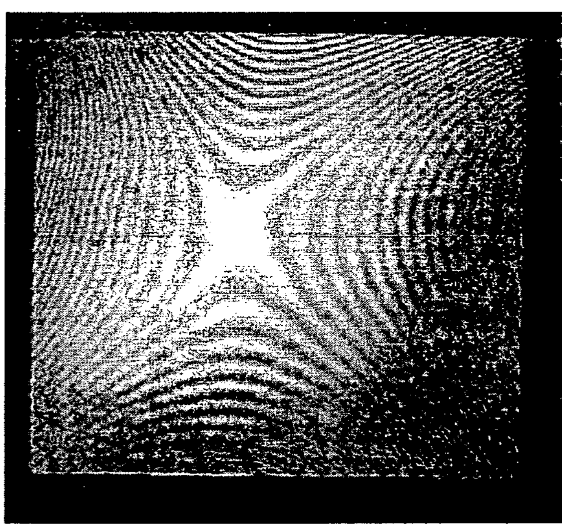

Figure 13 Double-pass interferogram for a 613 l/mm VPH grating with thin substrates.

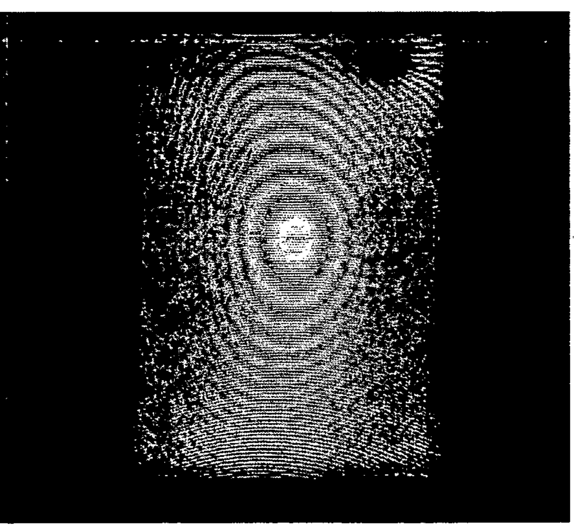

Figure 14 Double-pass interferogram for the 2400 l/mm VPH grating with thick substrates.

Figure 13 shows the double-pass wavefront performance in the 1st order of diffraction for the first VPH grating produced by Kaiser Optical Systems, Inc. for evaluation at NOAO. This grating is that described by Barden et al.[1] and is a 613 l/mm grating for use at 700 nm. The glass substrate and cover are both 3-mm thick BK7 glass plates. No significant effort was made to produce good wavefront performance and it is quite apparent that the grating has relatively poor imaging performance with about 14 waves of astigmatism. This is typical of the performance for cemented layers of thin glass that become distorted due to stresses from the optical cement holding them together.

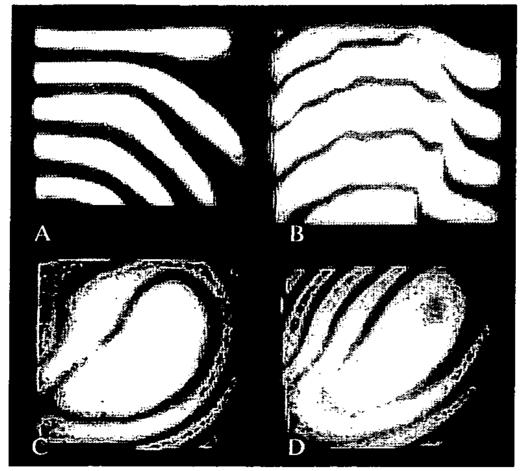

Figure 15 Double-pass interferograms for the grating components in the multiplex grating. A) 1620 l/mm 1st order pre-assembly. B) 1200 l/mm 1st order pre-assembly. C) 1620 l/mm 1st order post-assembly. D) 1200 l/mm 1st order post-assembly.

Many of the gratings produced for the NSF study were produced with much thicker substrates and cover plates (6-mm rather than 3-mm). The quality of the plates was specified to be ¼ wave. Unfortunately, the optical cement used to bond the plates together after fabrication of the grating still warped the final assemblies such that the wavefront became somewhat distorted. This is evident in Figure 14 which shows the double-pass performance of the 2400 l/mm grating with about 10 waves of error. Figure 15 shows the interferograms for the 1st order of diffraction for the grating components contained in the 1200/1620 l/mm multiplex grating. The wavefronts were measured for each grating prior to cementing them together and after the assembly was completed. Final performance for this grating is somewhat better than the other gratings with about only 2 waves of residual error.

Other groups have reported improvements in glass warpage due to cemting by using alternative optical cements such as Epo-Tek 301-2[6]. The use of such materials would allow a vendor to use high quality substrates with a reasonable expectation that the final grating assembly would have minimal wavefront error. The only drawback to this approach is the need to provide a sufficient number of such high-quality substrates so that the vendor can make a run of several gratings out of which the best is then selected as the final product.

Figure 16 Double-pass interferogram for the 450 l/mm VPH grism assembly.

Alternatively, the grating could be made on low quality substrates and then high quality outer plates cemented on to complete the assembly. Neglecting any wavefront error resulting from the holographic exposure in the presence of the low quality substrate, the wavefront error of the encased grating could be reduced. This practice, however, allows the introduction of additional bond lines and internal surfaces that may lead to an increase in scatter, reflections, and embedded imperfections.

Figure 16 shows the measured double-pass wavefront performance of the 450 l/mm grism which is a total stack of 4 glass elements. The final assembly shows about 2 waves of total error with dominant terms of astigmatism and power. Epotek

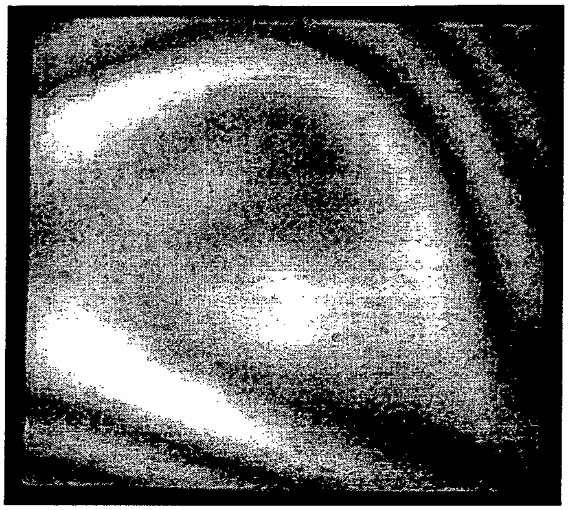

Figure 17 Double-pass interferogram for the 613 l/mm grating after it was post-polished showing 1.6 waves peak to valley distortion. Compare to Figure 13.

301-2 epoxy was used to mount the prisms to the grating assembly.

Another approach is to post-polish the outer surfaces of the final grating assembly. This would allow the use of lower quality and less expensive substrates for the making of the grating. The choice of optical cement would not be as critical as well. Additionally, the process of post-polishing could result in very high quality of the wavefront performance since the optician could null out any residual wavefront errors introduced by the grating hologram itself. The only significant drawback is that an AR coating would have to be deposited after the grating has been assembled. This eliminates the ability to use AR coating processes that utilize high temperatures (> 150 C) since such temperatures could destroy the gelatin layer of the grating.

An experiment of the post-polishing approach was made on the grating whose wavefront is shown in Figure 13. The double-pass wavefront performance of the thin, 613 l/mm VPH grating after it was post-polished is shown in Figure 17. Note the significant improvement in performance from 14 to less than 2 waves of error over the entire grating aperture! Much of this remaining error is likely a result of the thin assembly changing shape when it was released from the polishing fixture. One surface remained flat to better than ¼ wave. The second surface, however, distorted from 1/3 wave of flatness in the polishing fixture to 5 waves of power when the grating was released from the fixture.

5. SCATTERED LIGHT PERFORMANCE

Scattered light is another aspect of grating performance that can degrade the quality of the spectral data. Holographic SR gratings have always shown superior performance over ruled SR gratings with respect to scattered light. This is because the grating surface structure in a holographically generated SR grating is much smoother and more uniform than the structure created by a diamond ruling machine. One would expect that the scattered light performance of VPH gratings should be comparable to holographically

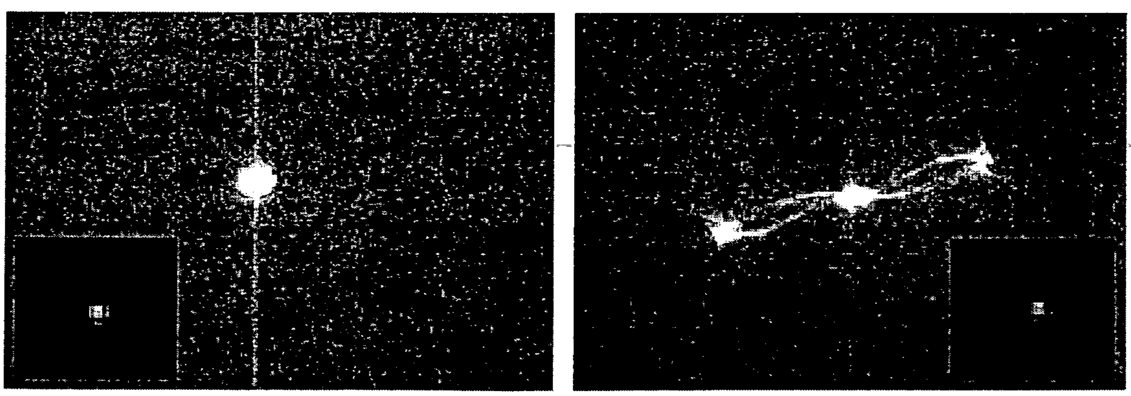

Figure 18 Measured scattered light of the 4800 l/mm VPH grating with prism substrates. The left image shows the input spot. The right image shows the spot imaged through the grating. A logarithmic stretch is used. The insets show the image profiles with a linear stretch.

generated SR gratings.

Figure 18 shows the images produced by the 4800 l/mm VPH grating with prism substrates. The left side of the display gives the point source imaged without the grating. Although the diffuse level of scattered light is not nearly as bad as is typically seen with ruled SR gratings, there is structured scattered light when the grating is introduced into the optical train. The level of intensity, per pixel, is about 1000 times fainter than the peak of the image. This is probably an order of 100 to 1000 times worse than what should be expected with holographic techniques. We suspect that the satellite images are ghost images introduced into the grating hologram by reflections off the surfaces of the transmissive collimators in the holographic exposure system. Improvement in the quality of the exposure collimators, apertures, and masks is expected to reduce the level of scattered light compared to what was found in this sample case.

6. CONCLUDING REMARKS

Volume phase holographic gratings have been fabricated and evaluated for use in astronomical applications. The VPH grating has demonstrated increased diffraction efficiency and wavelength tunability compared to its conventional surface relief cousins. Additionally, there exists the ability to obtain custom designed and fabricated gratings to address specific goals. Multiplexed VPH gratings offer a unique package wherein two gratings of different line frequencies are encapsulated in one assembly to simultaneously produce two independent spectra for analysis. Grisms, gratings encapsulated within prisms, with high line frequencies have been successfully made and tested. Wavefront distortion has been identified as an area requiring attention but improvements have been demonstrated within the scope of this effort and avenues for future work have been identified.

7. ACKNOWLEDGMENTS

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TABLE 1 -Differences between Applicants' claimed invention and '838 patent

Claim 1 of the Applicants' claimed invention	Corresponding element in the '838 patent	DIFFERENCES
a polarization separating sub-system, said polarization separating sub-system being optically disposed to receive an input optical beam of arbitrary polarization and also being capable of separating the input optical beam into a first optical beam of a first polarization and a second optical beam of a second polarization, said second polarization being distinct from said first polarization, and emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first (same) polarization,	birefringent element 200 or 201 disclosed in Fig. 3a of the '838 patent	the birefringent element 200 or 201 of Fig. 3a of the '838 patent emits two beams of different polarization while Applicants claim a system including a polarization separating sub-system capable of emitting at least two beams of the same polarization

at least one switchable diffraction grating	the polarization rotator 301_2 in Fig. 3a of the '838 patent	the polarization rotator 301_2 "produces a new beam, coaxial with the incident beam, having a specified new polarization angle" while, in the switchable diffraction grating, the direction of propagation of the output beam (or beams) deviates from the direction of propagation of the incoming beam
means for varying a diffraction efficiency of said at least one switchable diffraction grating	the means for switching the polarization rotator 301_2 in Fig. 3a	Since the polarization rotator 301_2 is not a switchable diffraction grating, the means for switching the polarization rotator 301_2 in Fig. 3a of the '838 patent are not means for varying a diffraction efficiency of the at least one switchable diffraction grating

a polarization recombining sub-system, said polarization recombining sub-system being capable of recombining the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first (same) polarization into at least one final output beam	the fourth birefringent element 203 in Fig. 3a of the '838 patent	The fourth birefringent element 203 in Fig. 3a of the '838 patent recombines two orthogonal polarizations into one output beam while polarization recombining sub-system of claim 1 in the Applicant's invention recombines at least two beams of the same polarization into at least one final output beam.